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TECHNICAL REPORT

Optical Measurement of High-Power LEDs

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Descriptor: Photometry
Colorimetry
Spectrophotometry

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1. Ein internationales Forum für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Messtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

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Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 2-63 of Division 2 "Physical Measurement of Light and Radiation" and has been approved by the Board of Administration as well as by Division 2 of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique CIE 2-63 de la Division 2 "Mesures Physiques de la Lumière et des Radiations" et a été approuvé par le Bureau et Division 2 de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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OPTICAL MEASUREMENT OF HIGH-POWER LEDS

Summary

Measurement results for light emitting diodes (LEDs) strongly depend on their thermal conditions. In order to achieve reproducible results with small uncertainties it is critical to accurately set and control the junction temperature of an LED during the time of optical measurement. This technical report describes the methods and procedures for measurement of high-power LEDs (HP-LEDs) under DC operation to acquire photometric, radiometric, and colorimetric quantities at a specified junction temperature.

MESURES OPTIQUES DE DELS HAUTE PUISSANCE

Résumé

Les résultats de mesures optiques de diodes électroluminescentes (LEDs) dépendent fortement de leur environnement thermique. Pour obtenir des résultats reproductibles avec de faibles incertitudes, il est critique d'ajuster et de contrôler précisément la température de jonction de la LED au cours de la mesure optique. Ce document technique décrit les méthodes et les procédures de mesures pour l'acquisition des données photométriques, radiométriques et colorimétriques de LEDs haute puissance (HP-LEDs), en mode DC (continu) et à une température de jonction spécifiée.

OPTISCHE MESSUNGEN AN HOCHLEISTUNGS-LEDS

Zusammenfassung

Messergebnisse für lichtemittierende Dioden (LEDs) hängen stark von den technischen Bedingungen ab. Um reproduzierbare Ergebnisse mit geringen Unsicherheiten zu erhalten, ist es entscheidend, die Sperrschichttemperatur der LED während der Dauer der optischen Messung exakt festzulegen und zu kontrollieren. Dieser technische Bericht beschreibt die Methoden und Prozeduren für die Messung von Hochleistungs-LEDs unter Gleichspannungsbetrieb, um photometrische, radiometrische und farbmétrische Größen bei einer festgelegten Sperrschichttemperatur zu erlangen.

1 Introduction

High-power light emitting diodes (HP-LEDs, see 3.1), most of which are white HP-LEDs for lighting applications, are now widely used in all types of solid-state lighting products. The technical report CIE 127:2007 (CIE 2007) has addressed many issues with regard to the optical measurement of LEDs in general, but it does not cover HP-LEDs. Optical measurement of HP-LEDs has been difficult because they are highly sensitive to their thermal conditions, in particular, their junction temperatures that vary significantly with operating conditions. LED manufacturers commonly measure HP-LEDs using a milliseconds-long single pulse or microseconds-long multiple pulse train without mounting the HP-LEDs on a heat sink, and it is assumed that the pulse is short enough so that the junction temperature, T_J , is close to the ambient temperature (typically 25 °C) (CIE 2017). Therefore, published HP-LED specifications normally refer to $T_J = 25$ °C. However, HP-LEDs in lighting applications are commonly operated in DC mode and at much higher temperatures (ranging from $T_J = 50$ °C to over $T_J = 120$ °C), where their photometric, radiometric, and colorimetric values deviate significantly. To meet the specifications of a lighting product, HP-LED users need to know the performance of an HP-LED at a known, hot condition.

To set or monitor the thermal condition of an HP-LED, “case temperature”, “pin temperature”, “board temperature”, “solder-point temperature”, or “heat sink temperature” is often used. Such a thermal reference is useful to ensure that the operating temperature of an HP-LED does not exceed the allowed maximum temperature or to reproduce the same thermal condition for a particular HP-LED. However, the reference is not always available and the measurement results of different HP-LEDs of the same type or the results of a different type of HP-LEDs cannot be directly compared. Also, an accurate measurement of temperature at such a reference point is often difficult because there is always an unknown thermal contact resistance between the reference point and the temperature sensor. Furthermore, the above reference temperature terms are vendor-specific.

On the other hand, the performance of an HP-LED is strongly correlated to its junction temperature, thus it is the ideal thermal reference for acquiring reproducible measurements and can be universally used for all types of HP-LEDs no matter how different the LED packages are. The junction temperature of an HP-LED can be measured. One example of such work (that also deals with measuring real thermal resistance) is described in (JEDEC 2010), (JEDEC 2012), and (Keppens et al. 2011).

The optical measurement method described in this report is straightforward (Zong and Ohno 2008). It uses the junction temperature of an HP-LED as the measurement reference condition. An HP-LED under test is directly set and controlled to a specified constant junction temperature and is operated in DC mode, therefore, all conventional optical instruments (such as sphere photometers, sphere-spectroradiometers, goniophotometers, goniocolorimeters, and gonio-spectroradiometers, etc.) designed for measurement of traditional light sources in the lighting industry can be used for measurement of HP-LEDs. In addition, the DC method is superior in terms of measurement uncertainties (even though it is slow) compared to the pulse methods which also use junction temperature as the thermal reference condition. For example, when a single pulse method is used, the measurement error due to the significant rise of junction temperature during a milliseconds-long single pulse (see Annex B) may be large, while the DC method completely eliminates such a measurement error (see Clause 4). Also, when a phosphor-converted white HP-LED is measured using a single-pulse method or a pulse-train method the measurement error resulting from the “cold” phosphor may be large. This is because under such a pulse-mode operation, the phosphor temperature of an HP-LED is close to its junction temperature, which is significantly lower (e.g. tens of degrees Celsius) (Yan et al. 2011) (Hwang et al. 2010) than the real temperature of “hot” phosphor when the HP-LED is operated in DC mode at the same junction temperature. While when the phosphor-converted white HP-LED is measured using the DC method, the HP-LED operates in the same way as it does in a typical lighting product, which completely eliminates the measurement error resulting from the “cold” phosphor. In principle, the above two measurement errors associated with the pulse methods can be analysed and corrected. However, such work is not

trivial. Alternatively, such measurement errors can be corrected by comparing the measurement result obtained using the pulse method with that obtained using the DC method.

This report describes setting and operating HP-LEDs at a specified junction temperature, various measurement setups, and measurement of photometric quantities (luminous intensity and total luminous flux), radiometric quantities (radiant intensity and total radiant flux), and colorimetric quantities.

The report aims to provide a guide for optical measurement of HP-LEDs for calibration and testing laboratories with emphasis on simplicity, excellent reproducibility, and small measurement uncertainties.

2 Scope

This technical report deals with methods used by calibration and testing laboratories for the measurement of optical quantities (including photometric, radiometric, and colorimetric quantities) of HP-LEDs, with focus on small uncertainties. The document covers measurement of HP-LEDs under DC operation only with the thermal condition referring to their junction temperatures. It does not cover those pulse methods with focus on measurement speed for testing facilities that perform fast measurement of a large number of LEDs (e.g. testing facilities used in LED production lines). Such methods are described in the CIE Technical Report "High-Speed Testing Methods for LEDs" (CIE 2017).

This document covers all single-diode HP-LEDs (including large-die HP-LEDs where the junction temperature may be different across the die). It also covers multiple-diode HP-LEDs (where multiple diodes are electrically connected in series or parallel, or both in series and parallel) as long as the total forward voltage is accessible, which include single-die, multiple-diode HP-LEDs, such as high-voltage LEDs (HV-LEDs) where many micro LEDs are integrated onto a single substrate, and multiple-die, multiple-diode HP-LEDs, such as chip-on-board (COB) HP-LEDs where multiple LED dies or surface-mounted device (SMD) LEDs are packaged onto a single metal-core printed circuit board (MCPCB) or a ceramic board. In the case of a large-die HP-LED or multiple-diode HP-LED the junction temperature used as the thermal reference is the average junction temperature. For phosphor-converted white HP-LEDs it covers both the contact phosphor type where phosphor is coated directly on the LED die and the remote phosphor type where phosphor is thermally insulated from the LED die.

This document does not cover AC-driven LEDs, organic light emitting diodes (OLEDs), LED modules, LED light engines, LED lamps, and LED luminaires. Those LED products are covered in other CIE publications, partly still in preparation. In particular:

- Characterization of AC-driven LEDs is described in the report of CIE TC 2-76 "Characterization of AC-driven LED Products for SSL Applications", currently still in preparation.
- LED products that comprise multiple dies or packages, and where the forward voltage is not accessible, are within the scope of the report of CIE TC 2-50 "Measurement of the Optical Properties of LED Modules and Light Engines", currently still in preparation.
- Organic LEDs (OLEDs) are covered by the report of CIE TC 2-68 "Optical Measurement Methods for OLEDs used for Lighting", currently still in preparation.
- The international standard CIE S 025/E:2015 deals with LED lamps, LED luminaires and LED modules (CIE 2015b).

3 Terms and definitions

For the purposes of this document the terms and definitions given in CIE S 017/E:2011 (CIE 2011a) and CIE S 017-SP1/E:2015 (CIE 2015a), and the following apply.

3.1

high-power LED

HP-LED

LED package that requires a heat sink or other means of thermal management for their normal operation

Note 1 to entry: A high-power LED is typically equipped with a dedicated cooling surface through which heat is transferred during normal operation.

3.2

temperature-controlled mount

TCM

mount with cooling and/or heating component(s) and with mounting holes, the temperature of which is set and regulated by a temperature controller

Note 1 to entry: A thermoelectric cooler/heater is often used in a TCM. For examples given in this document, a TCM is used to control an HP-LED's junction temperature.

4 Method for setting junction temperatures of HP-LEDs

HP-LEDs are measured under DC power at a constant forward current and a specified junction temperature. The forward voltage of a test HP-LED is first determined at a given junction temperature and a given drive current. Then the value of the forward voltage is used as the reference for feedback control of the HP-LED to be operated at the given junction temperature. Note in the case of a multiple-diode HP-LED, the forward voltage is the total forward voltage. This method requires a TCM, a fast current source to drive the test HP-LED, and a fast voltmeter to measure the HP-LED's forward voltage, $U_F(t)$. The following procedures are followed to set and operate a test HP-LED at a specified junction temperature.

NOTE 1 HP-LEDs are operated with a large current, thus the forward voltage, U_F , should be measured using the 4-wire sensing (Kelvin sensing) method. The use of 4-wire voltage sensing is especially important when the measured forward voltage is used to monitor the junction temperature of the test HP-LED.

- 1) Mount a test HP-LED on a TCM (e.g. using any carrier substrate recommended by the HP-LED vendor such as a MCPCB).
- 2) Set the temperature of the TCM, T_{TCM} , to be equal to the specified junction temperature, T_J , enable the TCM and wait a sufficient amount of time to allow for both the TCM and junction to fully stabilize, typically 1–2 minutes depending on the TCM and size/mass of the HP-LED. In reality, once the TCM is stable, the HP-LED is likely to be stable as well (unless it's a very fast TCM, which is unlikely, given that the TCM is designed to control HP-LEDs). The thermal status of the HP-LED can be monitored by measuring its forward voltage, $U_F(t)$, by applying a small monitoring DC current, I_M , typically one to a few milliamperes. An example of stabilization process of a TCM temperature and forward voltage of the attached HP-LED is shown in Figure 1.

NOTE 2 If I_M is too small, the current source and/or the HP-LED itself may not be sufficiently stable. If I_M is too large, self-heating of the HP-LED may not be negligible. For a 3-W HP-LED with a rated current $I_F = 1\,000\text{ mA}$, forward voltage $U_F = 3\text{ V}$ and assuming $I_M = 1\text{ mA}$, the radiant efficiency, η_e , is 50 %, and the thermal resistance, R_{th} , from the junction to the TCM is 10 K/W (a typical value for an MCPCB-mounted HP-LED), the rise of T_J due to self-heating is a negligible 0,015 °C.

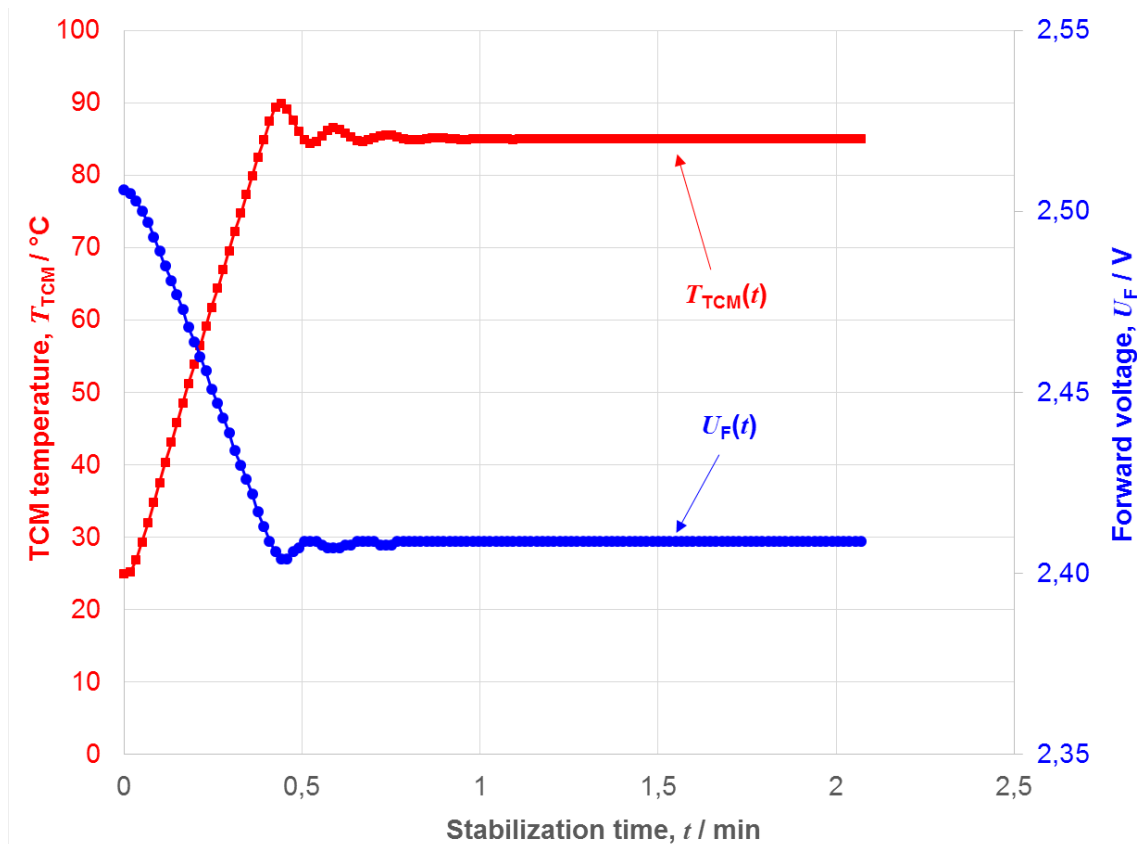


Figure 1 – Stabilization plots of a TCM temperature and forward voltage of the attached HP-LED with a monitoring current $I_M = 1$ mA

- 3) Apply the specified forward current pulse to the HP-LED with its peak current value equal to the specified DC operating current and start measuring the HP-LED's forward voltage, $U_F(t)$, immediately.
- 4) Determine $U_F(0)$ by fitting and extrapolating the $U_F(t)$ heating curve to $t = 0$. Note the shape of the heating curve depends on the properties of the test HP-LED and characteristics of the measurement tools used. An example for a heating curve is shown in Figure 2. The measured $U_F(t)$ function typically consists of two parts: an electrical only transient and a transient induced by the rising of the junction temperature, $\Delta T_J(t)$, due to heating. $U_F(0)$ can be obtained using the least-squares-fitting approach with a linear or exponential heating model. However, the preferred fitting method is the square root of time method, which can greatly reduce the fitting difficulty and increase fitting accuracy. Assuming a constant heating power at the p-n junction of the test HP-LED at the very beginning when the HP-LED is turned on, the relationship between rise of the junction temperature, $\Delta T_J(t)$, and square-root of the elapsed time, $\sqrt{t}$, is almost linear as shown in Figure B.1 (c) (Annex B). Thus, the drop of the forward voltage, $\Delta U_F(t)$, is also linear in $\sqrt{t}$ as shown in Figure B.2. This linear relationship is used to extrapolate $U_F(t)$ to $U_F(0)$ from the transient part induced only by the rising of the junction temperature. Details of this extrapolation are described in Annex B.

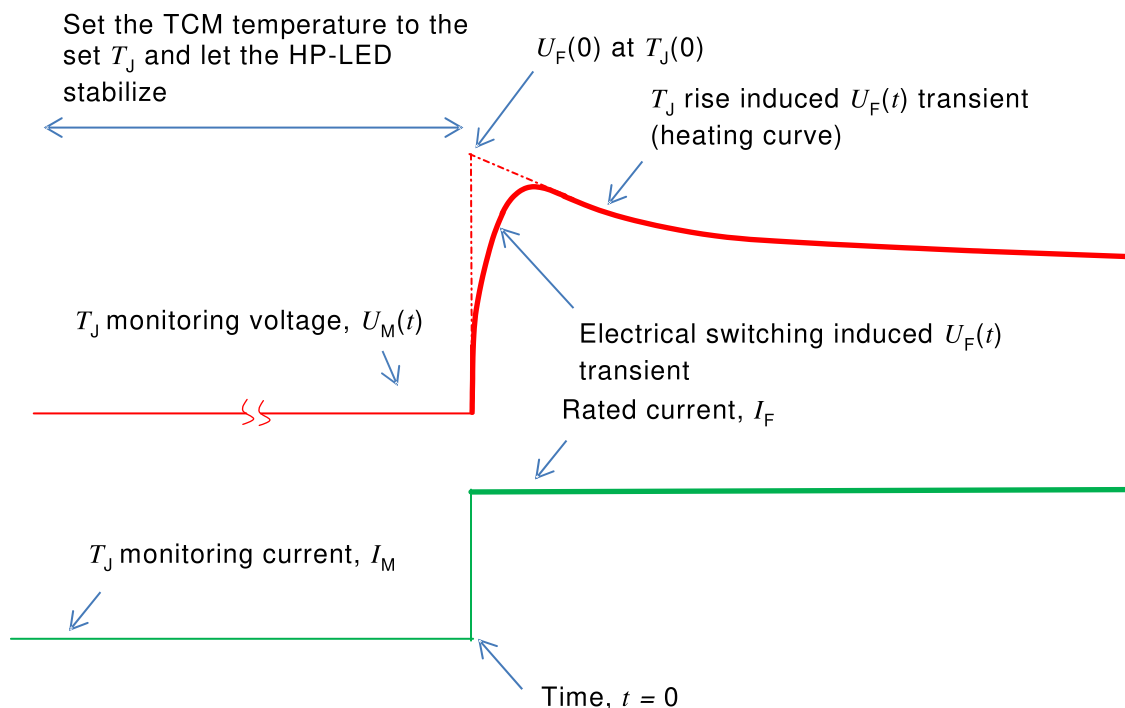


Figure 2 – Method to determine $U_F(0)$ by fitting and extrapolation of the heating curve, $U_F(t)$

- 5) Repeat steps (3) and (4) above to check the repeatability of $U_F(0)$ if necessary.
- 6) Turn on the HP-LED in DC mode with the specified operation current and adjust the TCM temperature so that the measured $U_F(t)$ is equal to $U_F(0)$, thus the test HP-LED is operated at the specified junction temperature, T_J . This process is shown in Figure 3.

NOTE 3 A TCM is typically slow to respond to power changes. When the test HP-LED is switched on suddenly with the full DC power it may be operated at a considerably higher temperature than the set junction temperature for a period of seconds, typically. This temporary “high-temperature” operation at the very beginning when the LED is turned on may be a concern if the estimated initial junction temperature, $T_{J,init}$, is higher than the allowed maximum junction temperature, $T_{J,max}$. The initial junction temperature of the HP-LED, $T_{J,init} (=T_{TCM} + P_H \cdot R_{th})$, can be estimated with the heating power, P_H (unit: W), and thermal resistance from the junction to the TCM, R_{th} (unit: K/W). To avoid a high initial junction temperature, $T_{J,init}$, the HP-LED should be turned on using a so-called DC-pulse operation mode, by which the level of the DC part of the current waveform is ramped up gradually and the $U_F(t)$ is measured at the peak current (the rated DC current level) of the pulse while the TCM is cooling down. The measured $U_F(t)$ is compared to the previously determined $U_F(0)$ to ensure that T_J does not go above the specified junction temperature by adjusting the ramping-up speed. Similarly, an HP-LED can be turned on by ramping up the duty cycle of the specified DC operating current from 0 % to 100 % while $U_F(t)$ is constantly monitored to ensure that the junction temperature, T_J , is below the specified junction temperature. Lastly, the temperature of the TCM can be lowered to the room temperature or the estimated temperature, $T_{TCM} (=T_J - P_H \cdot R_{th})$, before the HP-LED is switched on at its full power.

- 7) Perform optical measurements under the DC condition after the HP-LED is stabilized. The results obtained are values at the specified junction temperature, T_J .

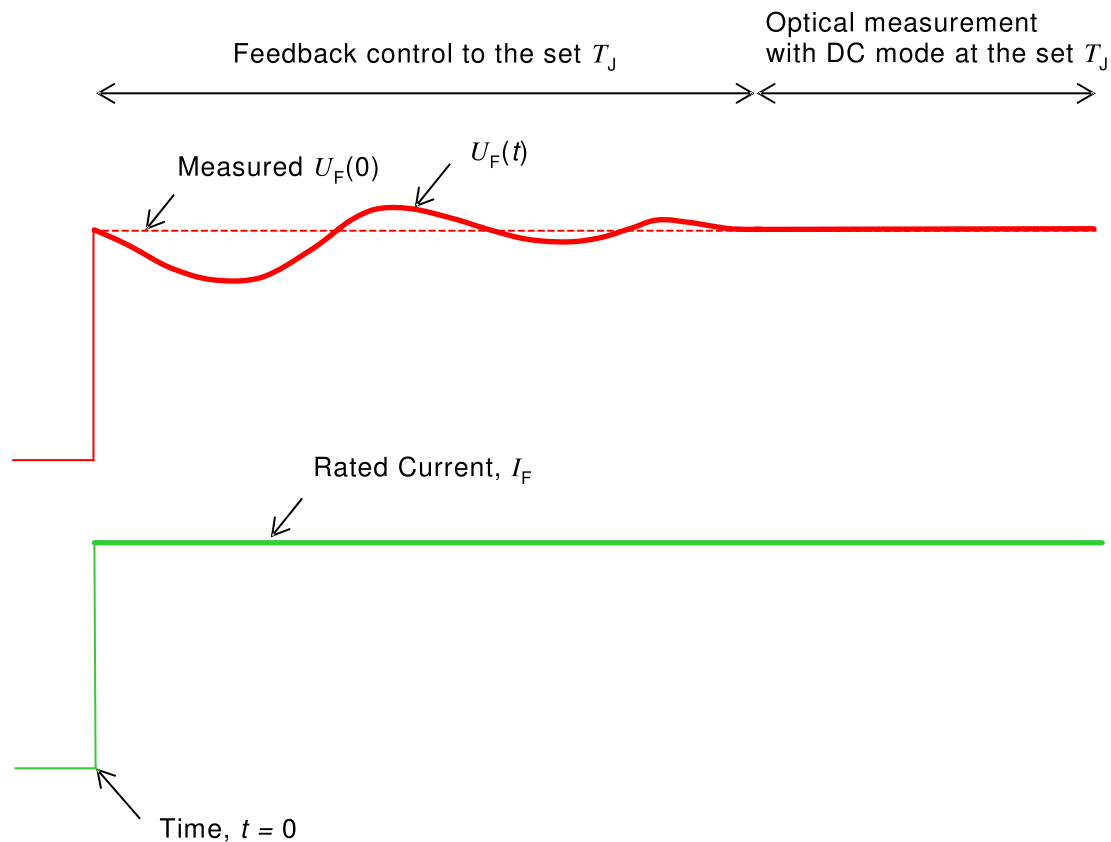


Figure 3 – Illustration of setting and controlling an HP-LED to a specified junction temperature

NOTE 4 When a large-die HP-LED (e.g. 5 mm × 5 mm die) is stabilized, the junction temperature may vary across the die; similarly, when a multiple-diode HP-LED is stabilized, the junction temperature may vary depending on the location of the individual diode. In both cases, however, the average junction temperature is still the same as the set junction temperature (Ying, Fu and Hong 2015).

NOTE 5 The measurement errors introduced by the variation of junction temperatures are considered negligible because the relationship between the small change of optical or electrical property and that of the junction temperature is typically within the linear range; therefore, the changes of optical or electrical property resulting from the variation of junction temperatures are mostly cancelled when the average junction is kept the same.

The $U_F(0)$ of an HP-LED used for controlling its junction temperature is stable for a short period of time, but it may change if it has been operated for hundreds of hours and/or it has been in storage for a long time (e.g. a year). In such a case, instead of using a previously determined $U_F(0)$ for a specified junction temperature, T_J , $U_F(0)$ should be re-determined before the optical measurement.

Since the junction temperature of an HP-LED is feedback-controlled using a TCM, the measurement result is typically neither sensitive to its ambient temperature nor dependent on its mounting orientation. However, for some phosphor-converted white HP-LEDs that have a high thermal resistance between their junction and phosphor, and remote-phosphor white HP-LEDs, the optical output may vary with the ambient air temperature due to its influence on the phosphor temperature (Gerloff et al. 2012). Thus, the ambient air temperature should always be recorded and reported as one of the measurement conditions.

HP-LEDs are commonly measured at a junction temperature, T_J , of 55 °C, 85 °C, or 115 °C, etc. In principle an HP-LED can be set to any junction temperature for optical measurement. However, the lowest junction temperature (around the typical room temperature of 25 °C), is limited by the allowed lowest $T_{TCM} (=T_J - P_H \cdot R_{th})$ (typically 15 °C) below which water

condensation may occur on the TCM and even on the MCPCB of the HP-LED. (Note that water condensation may not occur on the HP-LED itself because its temperature is higher than those of the TCM and MCPCB.) This limit on setting the junction temperature normally does not cause a problem since HP-LEDs are typically operated and thus measured at a much higher junction temperature than room temperature. To obtain optical properties at a junction temperature below room temperature, the test HP-LED may be measured using a pulse operation as described in (CIE 2017); alternatively, an extrapolation approach may be used based on a valid model for its thermal-optical characteristics, by which an HP-LED is first measured at several junction temperatures (e.g. 25 °C, 55 °C and 85 °C) that are higher than the specified junction temperature, and then the optical properties of the HP-LED at a specified junction temperature, are calculated by extrapolating the results measured at higher junction temperatures. Temperature dependence of measured total luminous flux and correlated colour temperature of an HP-LED and their third polynomial fittings are shown in Annex C, Figure C.3. An example of extrapolation is described in (Hulett 2015).

The method described above is straight-forward for setting the junction temperature, which is based on the determination of the forward voltage, $U_F(0)$. Under certain circumstances the junction temperature of an HP-LED may also be set for optical measurement by first measuring the thermal resistance of an HP-LED using an instrument designed for characterization and measurement of thermal resistances. Annex A describes such an alternative method.

5 Measurement setups

5.1 Optical bench

Characteristics of a light source, such as luminous or radiant intensity and colour are generally angle-dependent. Such quantities are required to be measured at a specified direction. The luminous or radiant intensity of an HP-LED is normally requested and measured for the direction perpendicular to its mounting base – the flat back surface of an unmounted HP-LED or the back of the MCPCB board of a mounted HP-LED. A setup on an optical bench for such a measurement is shown in Figure 4.

Unlike low-power LEDs, the high flux of an HP-LED allows measurement to be performed at a long distance for true luminous or radiant intensity. For this reason, it should be noted that the measured photometric quantity of luminous intensity must not be mixed up with the quantity “Averaged LED Intensity” defined for low-power LEDs for CIE Standard Conditions A and B in CIE127:2007 (CIE 2007). The Averaged LED Intensity is a test result at defined practical conditions by fixing the detector size and measurement distance. In contrast, the measured luminous intensity for an HP-LED is not restricted to a particular measurement condition.

NOTE The reference point for the distance measurement for determining luminous or radiant intensity is at the light-emitting surface of an HP-LED (near the top of the die or the top of the phosphor layer for a phosphor-converted white HP-LED). When the HP-LED has an encapsulating lens, the reference point for the distance measurement is at the location of the image of the light-emitting surface as shown in Figure 4 as an example. The exact location of the image can be determined using an optical instrument such as a microscope or other optical instrument. Furthermore, in order to obtain the true intensity, the measurement distance, d , from the reference point to the aperture of the detector must be long enough so that the aperture of the detector is uniformly illuminated, the uncertainty of the determination of the reference point is small compared to the required overall measurement uncertainty for intensity, and the point source approximation for the HP-LED is applicable. The measured true intensity can be verified using the inverse-square law on an optical bench or using other optical methods (Jacobs et al. 2014).